Accuracy Quantification of the Loci-CHEM Code for Chamber Wall Heat Transfer in a GO_2/GH_2 Single Element Injector Model Problem

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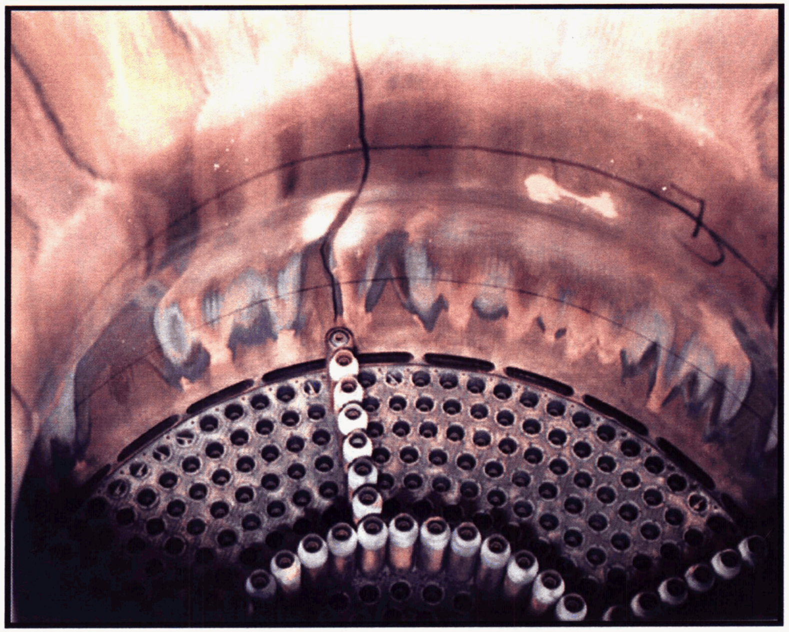
Overview

- Background
- Scope of the Current Effort
- Computational Tools
- CFD Model
- Results
- Conclusions
- Recommendations for Future Work

Background

The Need for Improved Injector Design Tools

- Issues with current injector design tools
  - 1-D, empirical
  - Result in costly, time consuming test, fail, fix development program



Environments are 3 dimensional

- Requirements for new injector design tools
  - **Fidelity**-must be able to calculate performance & 3-D environments as a function of injector design details and flow physics
  - **Robustness**-must be able to produce large numbers of solutions over a parametric space during the design phase
  - **Accuracy**- must be demonstrated to yield quantitative results

Background

The combustion CFD technology effort at NASA/Marshall Space Flight Center is guided by a Combustion Devices CFD Simulation Capability Roadmap. The Roadmap objective is:

> *To enable the use of CFD as a tool for the Simulation of Preburners, Ducting, Thrust Chamber Assemblies and Supporting Infrastructure in terms of Performance, Life, and Stability so as to affect the design process in a timely fashion.*

- If CFD is to be used as an injector design tool, code developers & code users must address this key issue:

  How should confidence (i.e. demonstrated accuracy capability) in simulations and modeling for design be critically addressed, and where necessary, improved?

- Verification & Validation of computational solutions are the primary means to quantify and build this confidence

Scope of the Current Effort

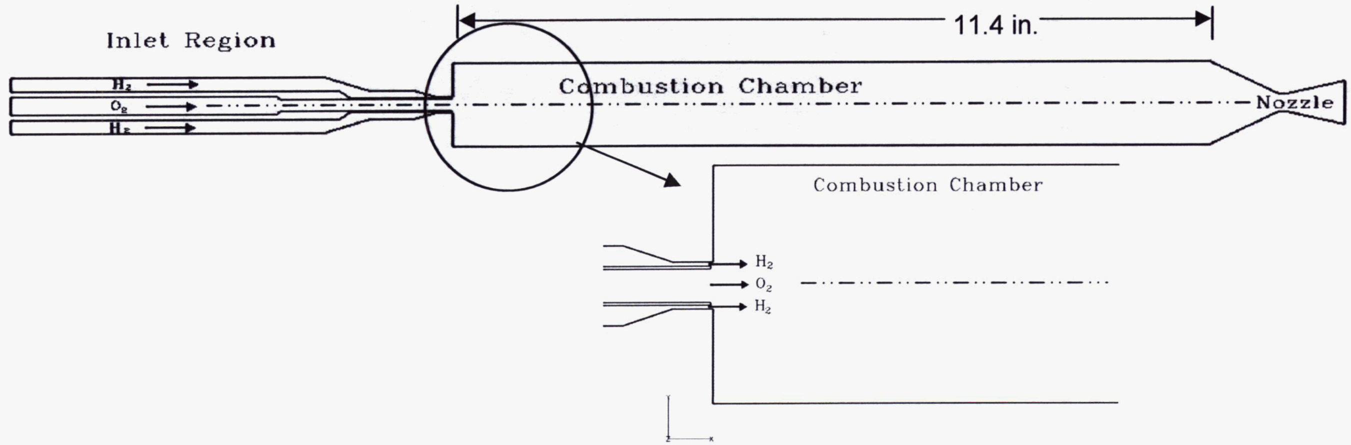
- Modeled the RCM-1 problem
- Goal of the effort
  - Achieve steady state solutions with demonstrated iteration and mesh convergence
  - Compare with data & critique results
- Computational effort consisted of the systematic evaluation of the effects of:
  - Turbulence models (k-ω, BSL & SST)
  - Preconditioning
  - Structured & hybrid meshes (with and without local refinement)
- It must be noted that NASA/MSFC sponsored the RCM-1 test problem and has used the test data to help guide this effort

Computational Tools

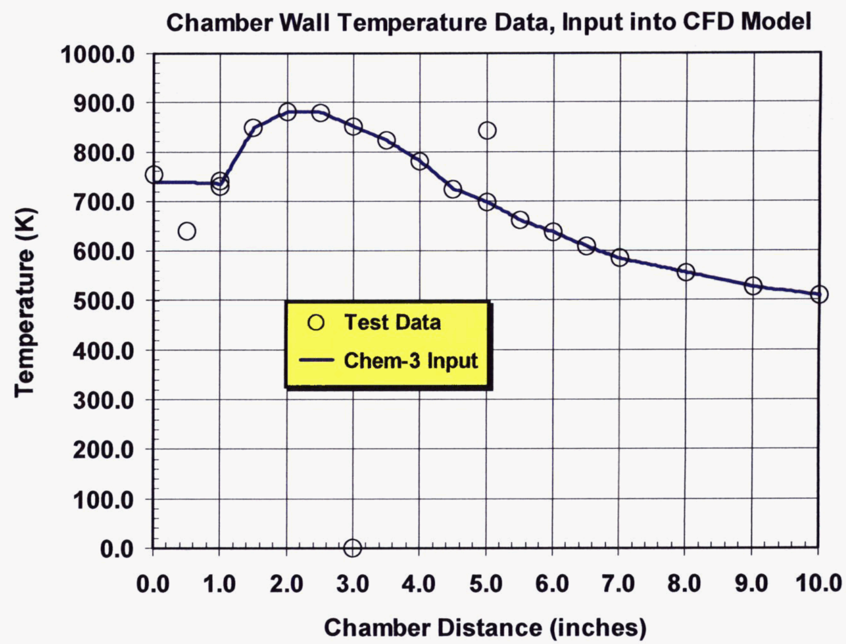
- Loci-CHEM CFD Code
  - C++ framework for automatically parallel applications
  - Finite-volume, unstructured, arbitrary polyhedra
  - Density-based, approximate Riemann solver with preconditioning
  - Finite rate chemistry, three low Re number k-omega turbulence models
  - Mentor's Baseline Model (BSL), Shear Stress Transport model (SST) and original Wilcox model (1988)
  - Typically require first cell from wall $y+$ values from 1 to 0.1.
- Gridgen (Pointwise, Inc., Fort Worth, Texas)
  - CFD mesh generation, structured, unstructured, hybrid structured/unstructured
  - In use at NASA/MSFC for over 15 years

Computational Model

Experimental Boundary Conditions

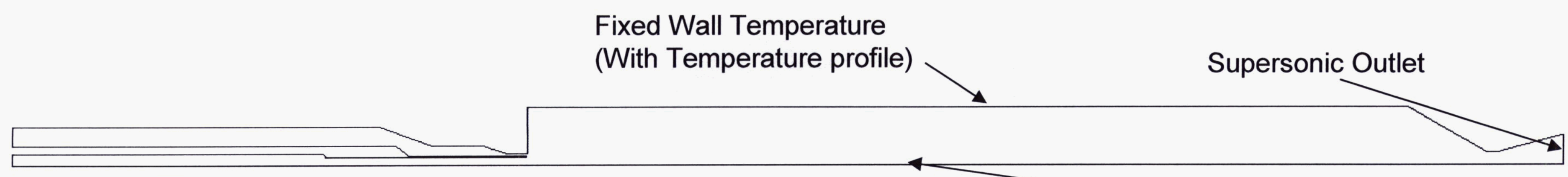


Inlet Boundary Conditions		
Inlet Parameter	Oxygen Tube Inlet (from OPB)	Hydrogen Annulus Inlet (from FPB)
Species Mass Fraction	0.9445 O_2 0.0555 H_2O	0.5977 H_2 0.4023 H_2O
Mass Flow	0.0905 kg/s	0.0331 kg/s
Temperature	767.59 K	798.15

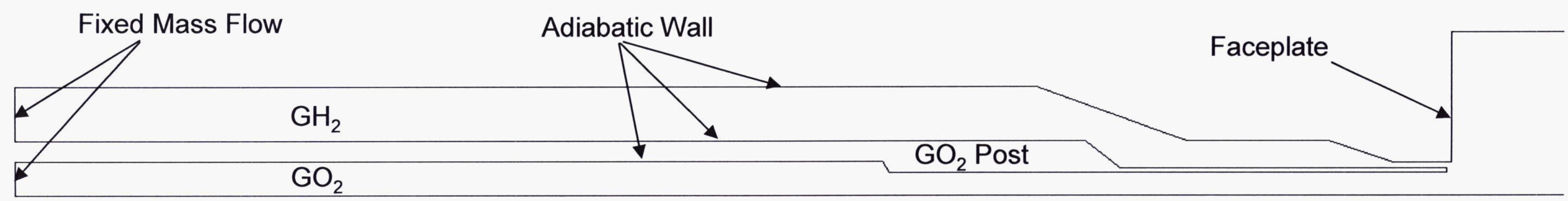


Computational Model

Computational Boundary Conditions



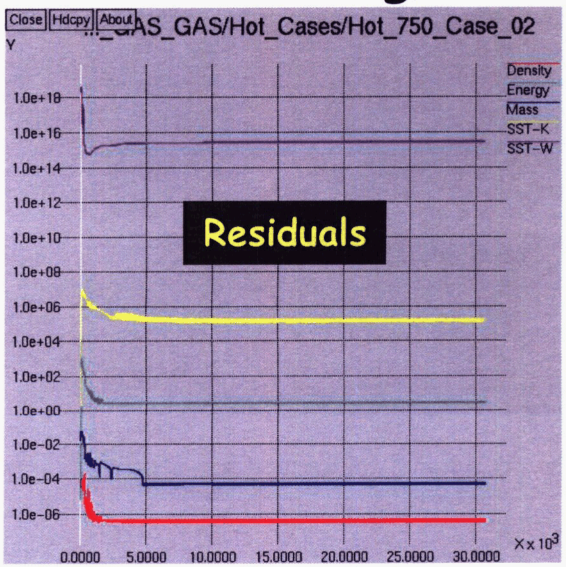
Chamber Details

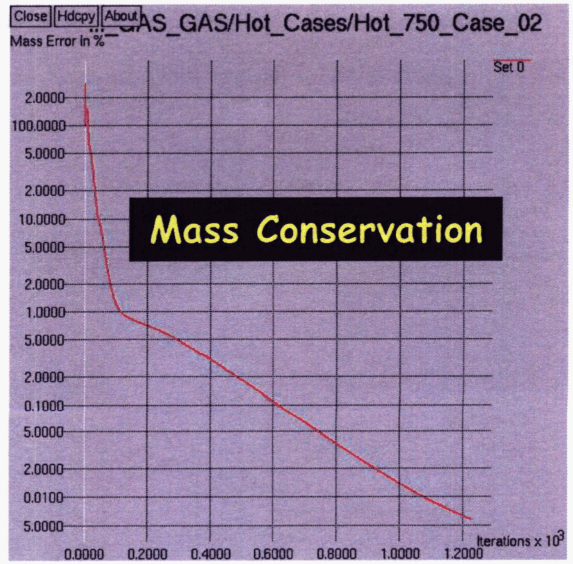


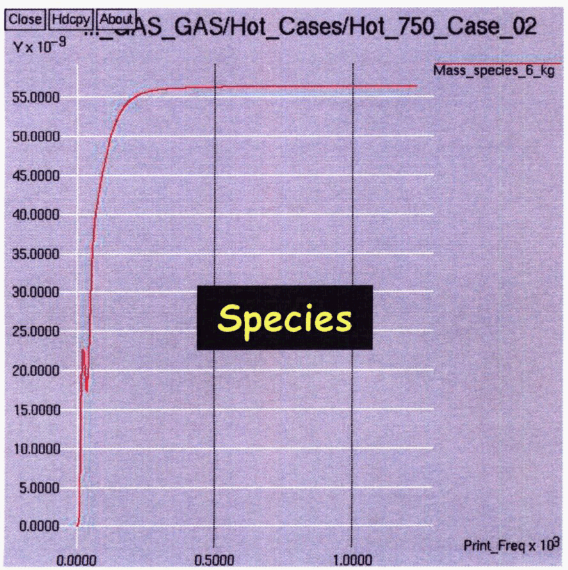
Single Element Details

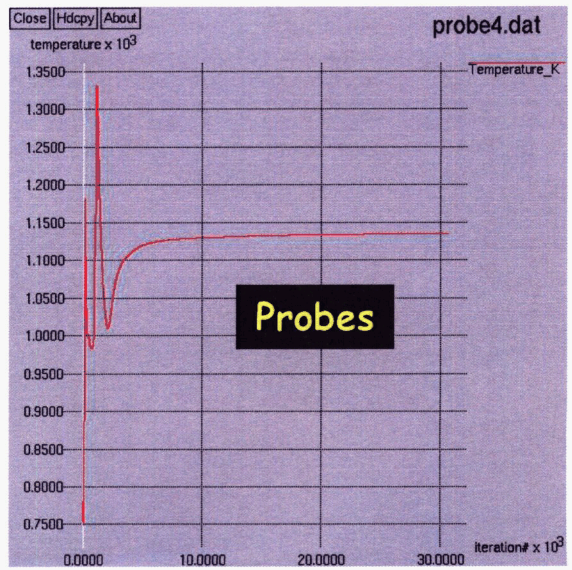
Computational Model

- **Iteration Convergence**



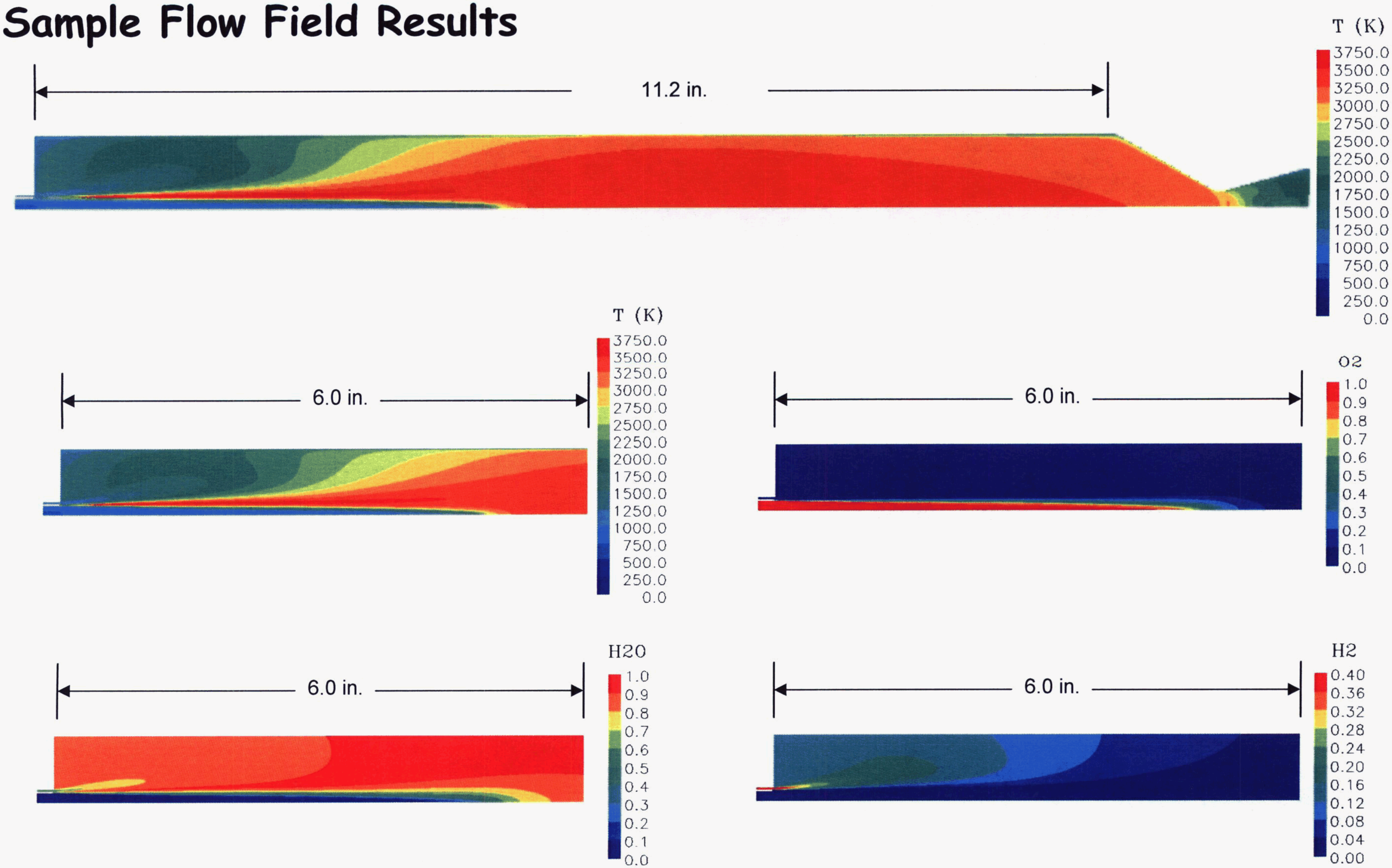






Computational Model

Sample Flow Field Results



Results

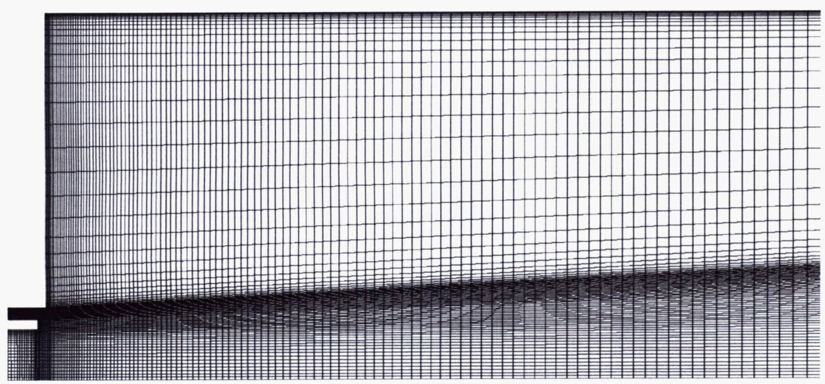
Calculation Progression

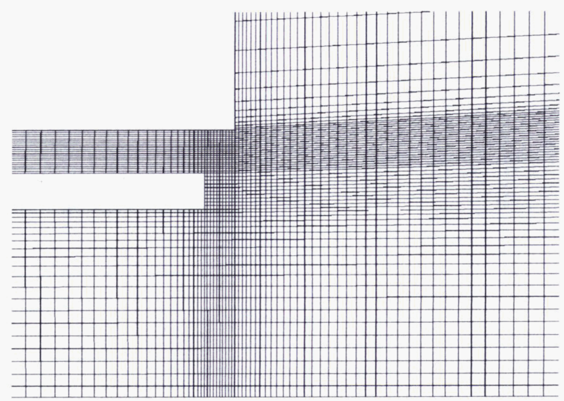
- Case 1--initial turbulence model selection (course structured mesh—no preconditioning, all 3 turbulence models)
- Case 2—final turbulence model selection (finer hybrid mesh—no preconditioning, all 3 turbulence models)
- Case 3—evaluate effect of preconditioning (on mesh 2)
- Case 4—mesh refinement studies (starting with mesh 2)
  - In the unstructured volume (Case 4a)
    - Refine all but flame region (mesh 3)
    - Refine flame region only (mesh 4)
    - Combination of above (mesh 5)
  - In the structured boundary layer (Case 4b)
    - Evaluate y^+ and stretch rate effects ($1.2 \rightarrow 1.1$) (mesh 6)
    - Evaluate stretch rate effects (mesh 7)
    - Evaluate axial spacing effects (mesh 8)
      - to lead to better actual Δs vs. desired Δs (Gridgen effects)

Results—Case 1

Initial Turbulence Model Selection

- Mesh 1
  - Structured mesh with 104,094 points and 51,030 cells.
  - It has a y^+ of approximately 1.3 or less in the chamber section.
  - The mesh was generated using Gridgen with the first point off the chamber wall set at 10^{-4} inch and used the TANH distribution function to set the grid point distribution.
- Mesh snapshots

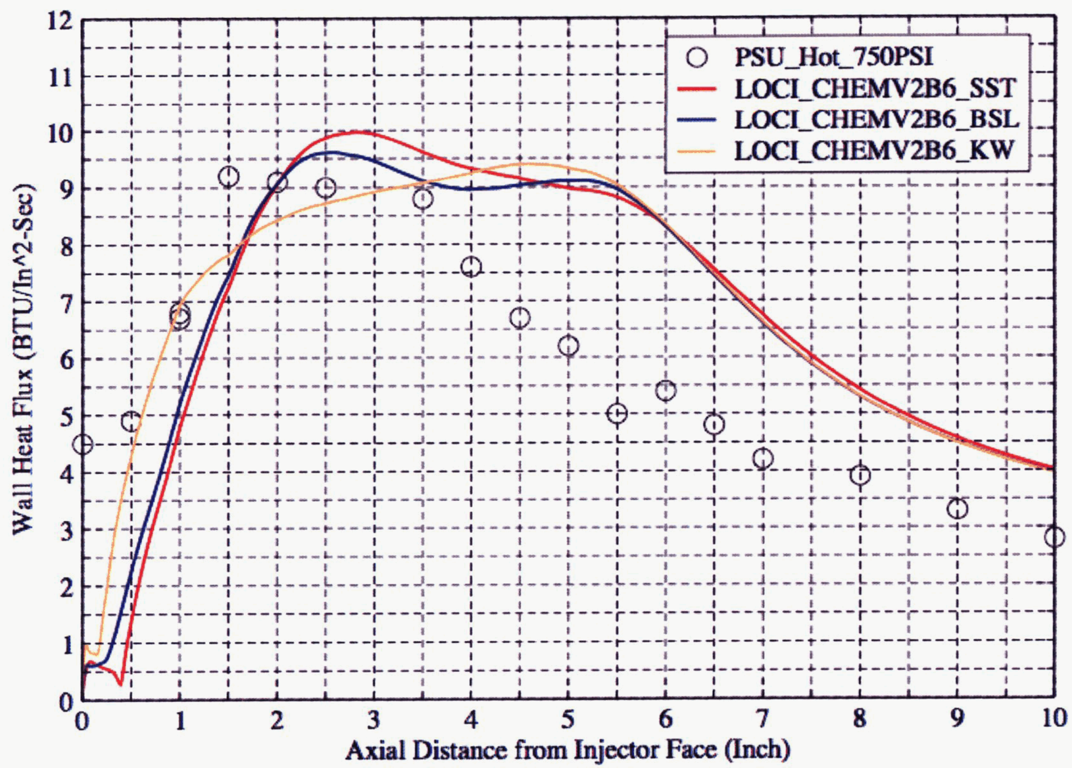




Results—Case 1

Initial Turbulence Model Selection

- Loci-CHEM Version 2.0 Beta 6 was used for Case 1 without preconditioning
- SST & BSL show best comparison with data in terms of magnitude and location of peak heat flux



Results—Case 2

Final turbulence model selection

Mesh 2 description
- 496,496 cells total
- Initial cell spacing (Δs)
  - Along GOX/GH_2 post
    - Desired: 1.10×10^{-6} in
    - Actual: Ranges from 1.2×10^{-5} in. (Fluid Entrance Region) to 1.1×10^{-6} in. (Post-Tip Region)
  - Along GH_2 OD, Faceplate, Chamber Wall, Nozzle
    - Desired: 7.50×10^{-6} in
    - Actual: Ranges from 7.7×10^{-6} in. (0.0 – 5.0 inches) to 1.8×10^{-5} in. (5.0 – 10.0 in.)
- Extrusion Stretch Rate along all walls is 1.20
  - Along GOX/GH_2 post: 1.175
  - Along GH_2 OD, Faceplate, Chamber Wall, Nozzle: 1.20
- Y^+ values
  - Injector region: < 0.50 except at one diameter reduction, 0.75 max
  - Faceplate/Chamber Wall:
    - < 0.10 from 0.0 – 5.0 in
    - ranges from 0.10 to 0.25 from 5.0 – 10.0 in.
  - Nozzle: ranges from 0.50 to 3.30

Results—Case 2

Final turbulence model selection

Mesh 2 description: 496,496 cells total

Boundary Layer Effects on Faceplate, Chamber Wall			
Stretch Rate	Initial ds (desired)	Initial ds (actual): 0 - 5 in	Initial ds (actual): 5 - 10 in
1.20	7.5×10^{-6} in	7.7×10^{-6} in	1.8×10^{-5} in
Boundary Layer Effects on GOX/GH_2 post			
Stretch Rate	Initial ds (desired)	Initial ds (Actual) (Entrance)	Initial ds (Actual) (Post-tip)
1.175	1.10×10^{-6} in	1.20×10^{-5} in	1.10×10^{-6} in
Interior Unstructured Mesh Effects			
	Min Edge Length	Max Edge Length	Boundary Decay Effect
	3.20×10^{-4} in	1.20×10^{-2} in	0.995

Results—Case 2

Final turbulence model selection

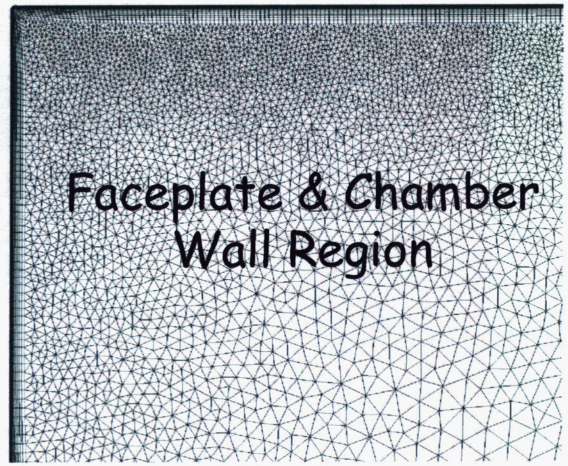
Mesh 2 description: 496,496 cells total

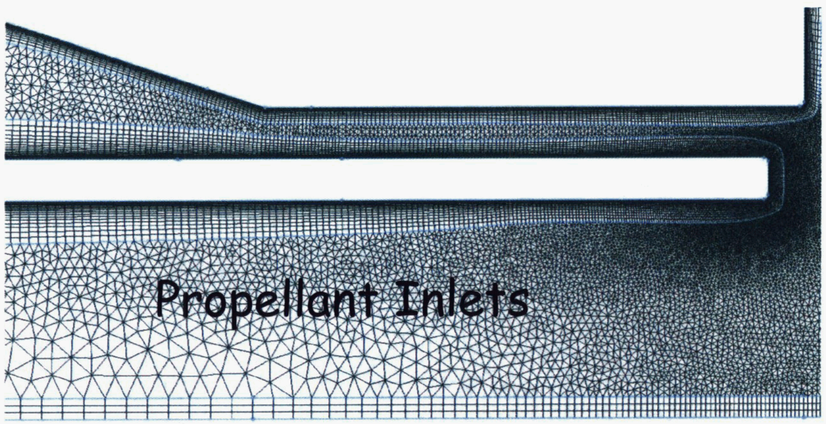
	Boundary Layer Effects in Faceplate, Chamber Wall			
Description	Stretch Rate	Initial ds (desired)	Initial ds (actual): 0 - 5 in	Initial ds (actual): 5 - 10 in
Baseline Meshes 2 - 5	1.20	7.5×10^{-6} in	7.7×10^{-6} in	1.8×10^{-5} in
Reduce Initial ds and Stretch Rate - Mesh 6	1.10	2.5×10^{-6} in	2.5×10^{-6} - 1.1×10^{-5} in	1.3×10^{-5} in
Reduce Stretch Rate - Mesh 7	1.10	7.5×10^{-6} in	7.5×10^{-6} - 3.5×10^{-5} in	3.8×10^{-5} in
Reduce Initial ds, Stretch Rate, Axial Spacing - Mesh 8	1.10	2.5×10^{-6} in	2.5×10^{-6} in	6.2×10^{-6} in

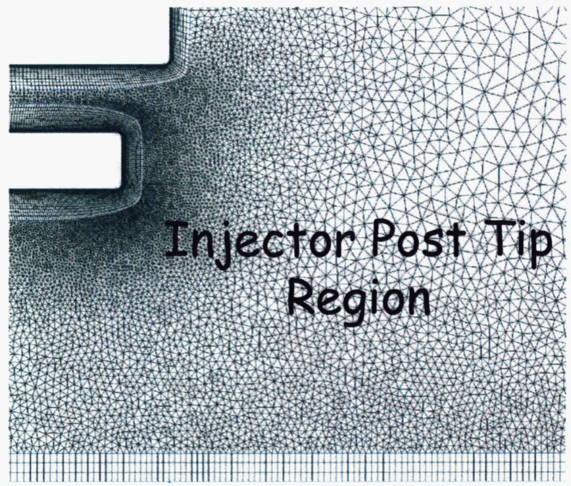
	Boundary Layer Effects in GOX/GH_2 post			
	Stretch Rate	Initial ds (desired)	Initial ds (Entrance)	Initial ds (Post-tip)
All Meshes	1.175	1.10×10^{-6} in	1.20×10^{-5} in	1.10×10^{-6} in

Results—Case 2

Final turbulence model selection

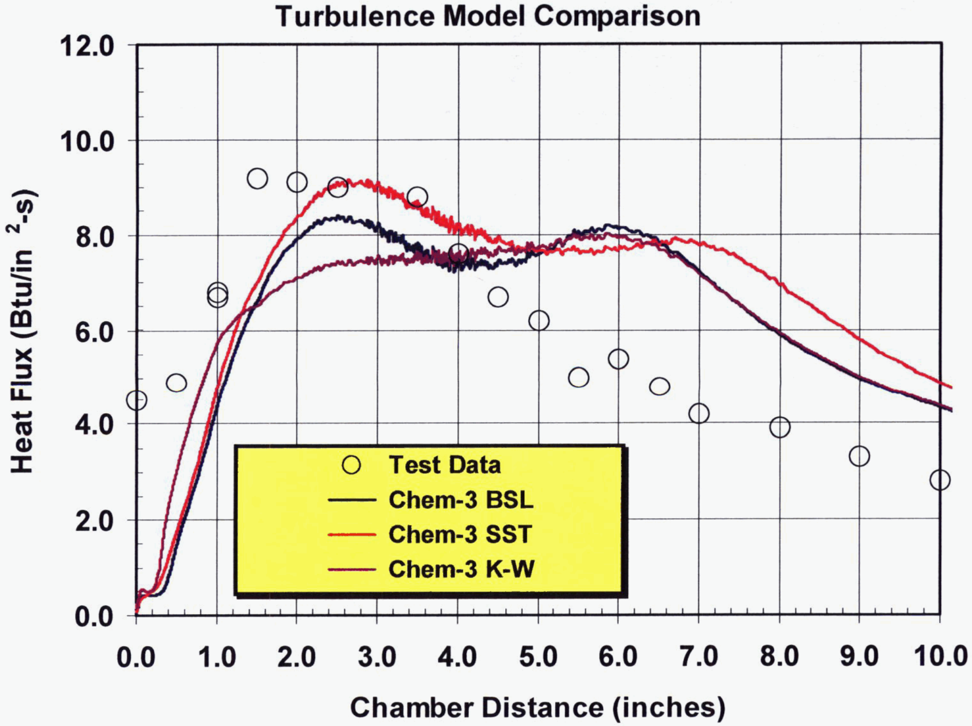






Results—Case 2

Final turbulence model selection

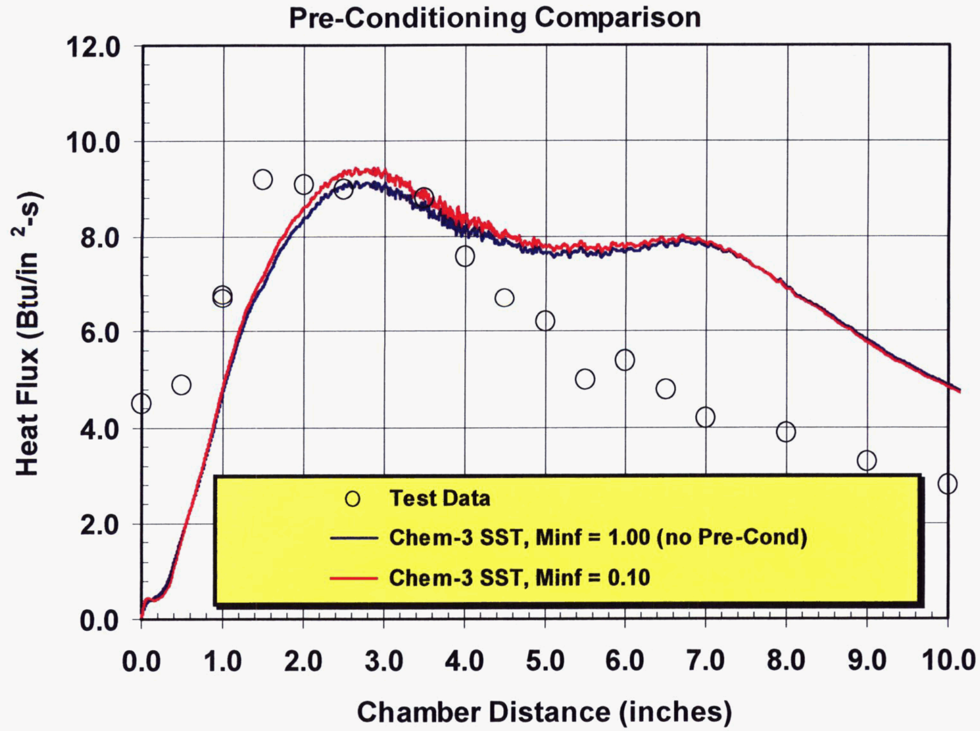


- Key issue is ability to predict heat flux rise rate and peak heat flux in the near-injector region of the chamber. This is a major drawback of empirical methodologies.
- All 3 models predict the heat flux rise rate fairly well
- The SST model better predicts the peak heat flux
- All 3 models over-predict downstream heat flux by 30-100%
- The SST model performs better in the important head end region

Results—Case 3

Preconditioning effect

- Results from Mesh 2 using SST turbulence model

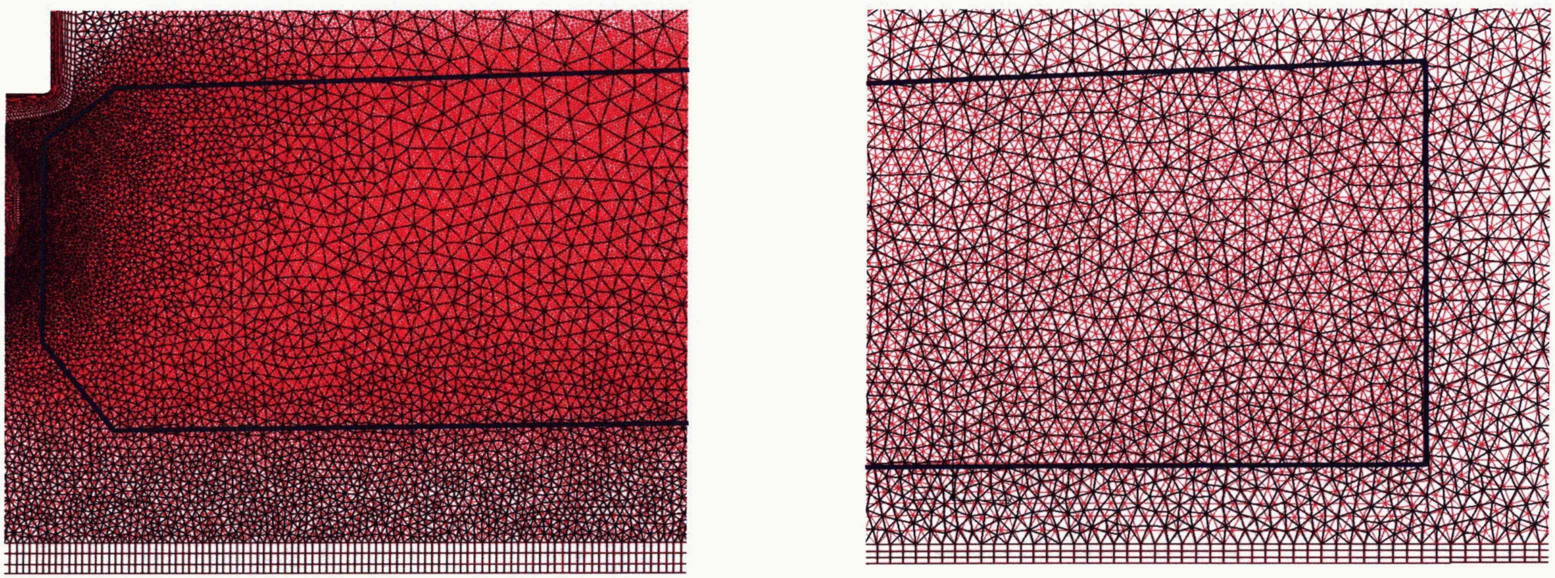


- Preconditioning improves matrix solution results at lower Mach numbers, without any loss of accuracy at higher Mach numbers
- Preconditioning provides faster convergence (3 - 5 times faster in some cases)
- Preconditioning has no real effect on result accuracy

Results—Case 4a

Unstructured Volume Mesh Refinement Studies (all with SST turbulence model and Preconditioning)

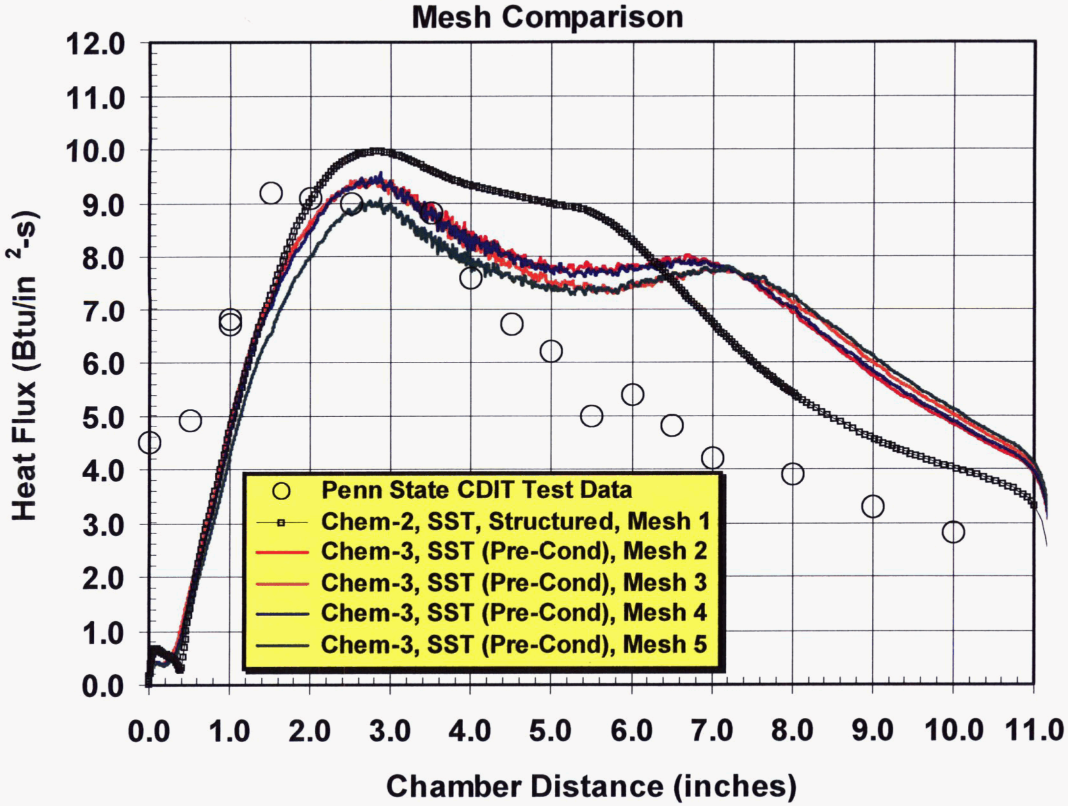
- **3 unstructured volume mesh refinements (starting with Mesh 2, ~496 K cells)**
  - Mesh 3—global reduction in unstructured mesh maximum cell length (724,936 cells)
  - Mesh 4—local reduction in mesh maximum cell length in shear layer region only by creating a separate "box" in that region (782,872 cells)
  - Mesh 5—combination of Mesh 4 & 5 effects (993,848 cells)



Examples of Mesh 5 refinements (black=Mesh 2, red=Mesh 5)

Results—Case 4a

Unstructured Volume Mesh Refinement Studies (all with SST turbulence model and Preconditioning)

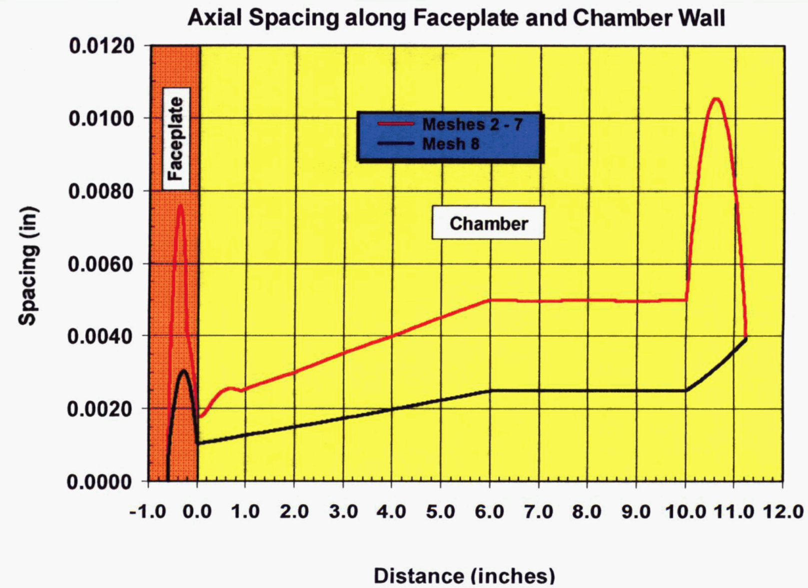


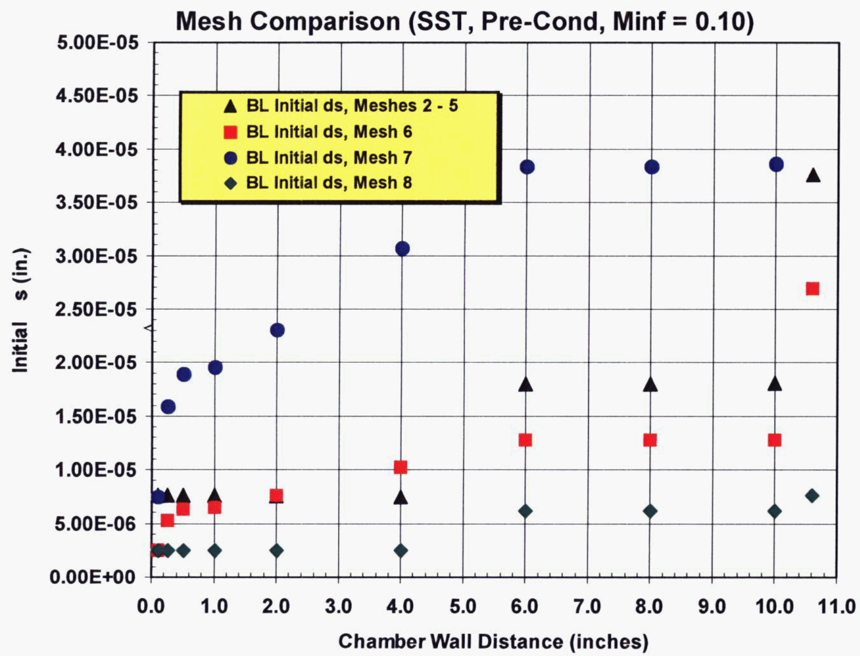
- Mesh refinements show relatively minor quantitative effects
- Mesh 5 peak heat flux is approximately 5% lower than results for meshes 2-4
- Mesh 5 heat flux is 5-10% higher in the 7-10 inch downstream region

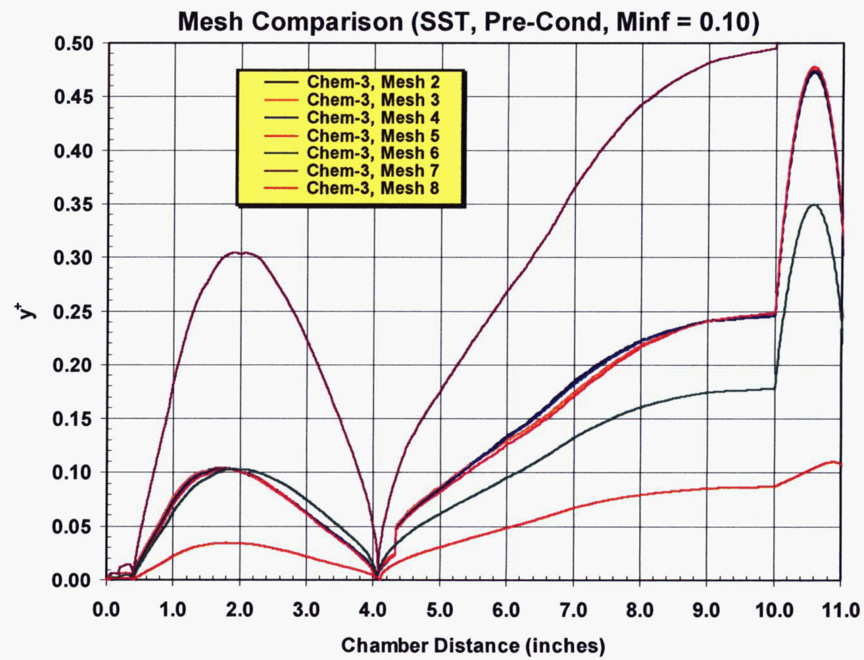
Results—Case 4b

Structured Boundary Layer Mesh Refinement Studies (all with SST turbulence model and Preconditioning)

- 3 structured boundary layer mesh refinements (starting with Mesh 5)
  - Mesh 6 - evaluate y^+ (reduced initial Δs) and stretch rate effects ($1.2 \rightarrow 1.1$) - 1,092,476 cells
  - Mesh 7 - evaluate stretch rate effects ($1.2 \rightarrow 1.1$) - 1,045,616 cells
  - Mesh 8 - evaluate axial spacing effects which helped reduce initial Δs - 1,446,093 cells

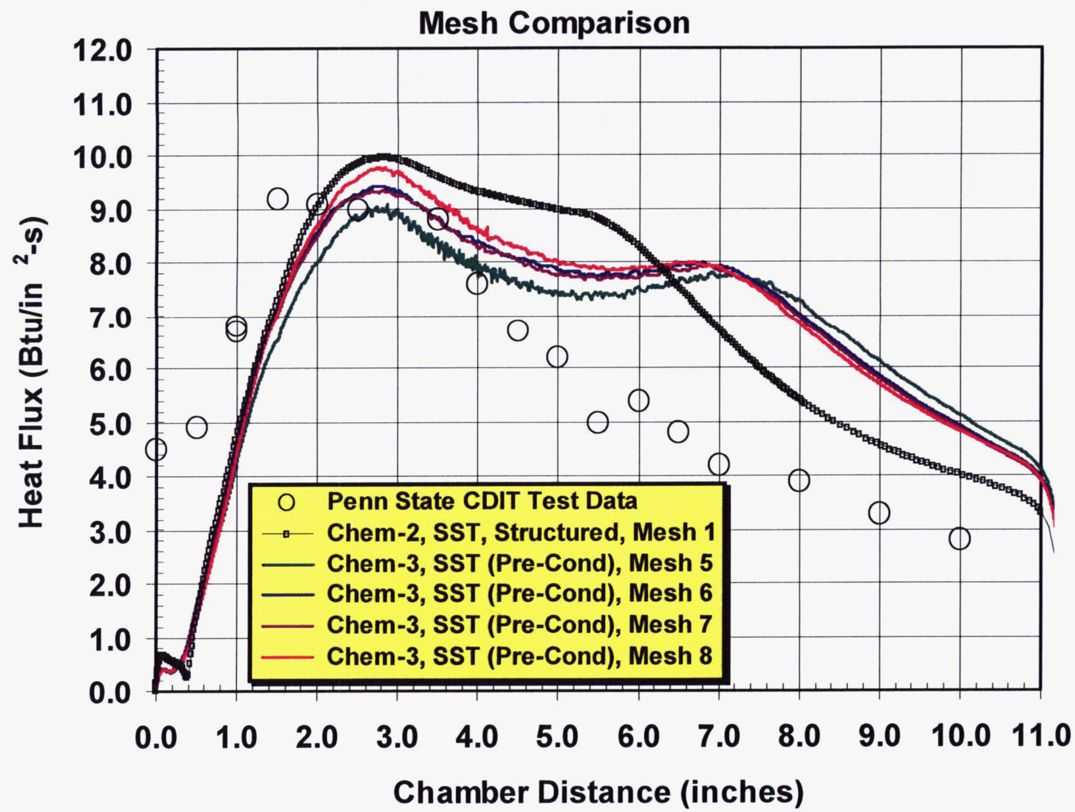






Results—Case 4b

Structured Boundary Layer Mesh Refinement Studies



- Boundary Layer Mesh refinements show relatively minor quantitative effects (5-10%)
- Change in axial spacing has most effect

Conclusions

- All solutions with Loci-CHEM achieved demonstrated steady state and mesh convergence
- Preconditioning
  - No significant effect on solution accuracy
  - Typically yields a 3-5x solution speed-up
- Turbulence model—SST model chosen
  - Superior performance, relative to the data in the head end region, for the rise rate and peak heat flux
  - Slightly worse than others in the downstream region where all over-predicted the data by 30-100%
- Mesh Studies
  - Systematic mesh refinement in the unstructured volume and structured boundary layer areas produced only minor solution differences
  - Mesh convergence achieved
- Overall, Loci-CHEM
  - Satisfactorily predicts heat flux rise rate and peak heat flux
  - Significantly over predicts the downstream heat flux

Recommendations for Future Work

- Further decomposition of the problem into unit physics problems
  - Series of simple, representative jet problems
  - Series of simple, representative heat transfer problems
- Continue mesh studies in the direction of coarser grids
- Determine the cause of the over prediction of the downstream heat flux
- Run the problem in the unsteady mode